CHARACTERISTICS OF EXPANSIVE PRESSURE OF AN EXPANSIVE DEMOLITION AGENT AND THE DEVELOPMENT OF NEW PRESSURE TRANSDUCERS

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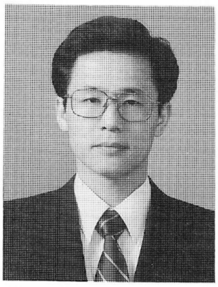
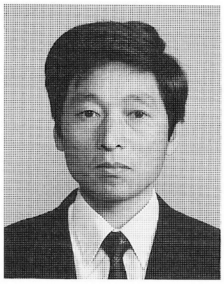
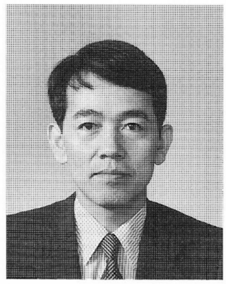
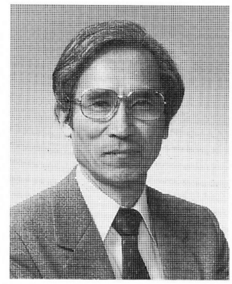

Tetsuo HARADA | Koichi SOEDA | Takashi IDEMITSU | Akira WATANABE

ABSTRACT

Expansive demolition agents are widely used to demolish massive rocks and concrete structures. To execute the demolition work rationally using expansive demolition agents , it is important to estimate the expansive pressure precisely and to determine its action on the inner surface of a borehole. The authors have developed new pressure transducers that can directly measure expansive pressure in a borehole. Several variables affecting the nature of expansive pressure in a borehole were also investigated with these transducers. As a result, the following were found: (1) Expansive pressure is transmitted in a manner similar to that of fluid; (2) The influence of the physical restraint of surrounding materials is very small; (3) The expansive pressure depends on thermal conditions including ambient temperature, but when the relationship between expansive pressure and the degree of hydration of CaO is plotted on the same curve, they are found to be independent of temperature.

Keywords: pressure transducer, expansive demolition agent, expansive pressure

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1. INTRODUCTION

Some expansive demolition agents were developed originally in Japan to demolish concrete and massive rock without vibration, noise, or other forms of pollution. They have achieved satisfactory results steadily as non–explosive demolition method since then it has been on the market from 1979. Safe demolition is possible using high expansive pressure. High expansive pressure gradually builds up by hardening and expansion of the slurry, which is a mixture of the agents and water; follow by pouring into boreholes in concrete or rock. After several hours, cracks occur slowly between each of two boreholes due to the high expansive pressure. To estimate the cracking time and determine the distances between each boreholes precisely, it is essential to clarify the behavior of expansive pressure which play an important role of demolition.

First of all, the authors have developed new pressure transducers to measure the actual behavior of expansive pressure acting on the inner surface of the boreholes directly. With these transducers, the characteristics of expansive pressure were investigated experimentally. Although the authors have already reported on some prominent characteristics of expansive pressure in a previous paper [1]; this paper contains new experimental results and also the mechanics of expansive generation with expansive demolition agents and a theoretical discussion of the mechanics.

This paper is summarized part of the doctoral dissertation of the first author presented to the University of Tokyo, furthermore and newly obtained results are added.

2. MEASURING METHOD OF EXPANSIVE PRESSURE

A necessary and complex problem is how to measure the expansive pressure of hardened material exactly and directly, which are acting on the surface of the boreholes, since the agents mixed with water harden like concrete giving rise to expansive pressure. Some measuring methods of expansive pressure developed by the authors and is shown as follows.

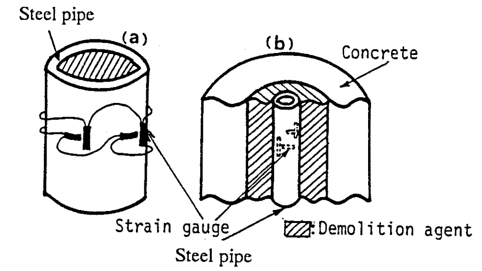
2.1 Outer pipe method and inner pipe method

The expansive pressure acts as the internal pressure on the inner surface of a steel pipe after filling with the slurry of the agents as shown in Fig. 1(a). Internal expansive pressure (p_o) is calculated by Eq. (1) using the circumferential strain ε_θ, axial strain ε_z measured by the orthogonal strain gauges at the outer surface on the steel pipe. In this method, a steel pipe with orthogonal strain gauges attached is treated as a pressure transducer. This method is called the "Outer Pipe Method". It is simple to measure the expansive pressure in practice; however, the magnitude of the expansive pressure may be slightly different from the one actually acting on the inner surface of the boreholes, since the part to be demolished is a steel pipe and this is an indirect measuring method.

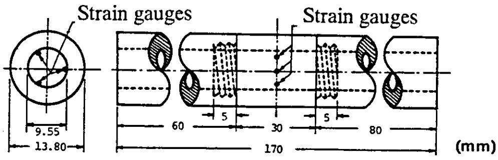
$$p_o=\frac{E_s(k^2-1)}{2(1-\nu_s^2)}(\varepsilon_\theta+\nu_s\varepsilon_z) \qquad (1)$$

$$p_i=-\frac{E_s(k^2-1)}{2(1-\nu_s^2)k^2}(\varepsilon_\theta+\nu_s\varepsilon_z) \qquad (2)$$

where, E_s is Young's modulus of the steel pipe,
ν_s is Poisson's ratio of the steel pipe, and
k is the ratio of the outer diameter to the inner one (k = outer diameter/inner diameter).



(a) Outer pipe method (b) Inner pipe method



(c) Sensory part of inner pipe method

Fig. 1 Schematic Diagram of Outer and Inner Pipe Method

On the other hand, one of newly developed method to measure the expansive pressure acting on the inner surface directly is shown in Fig. 1(b). This method uses an embedded transducer made of steel pipe in which orthogonal strain gauges are attached on the inner surface. This transducer can be located in the center of a borehole filled with slurry while the external expansive pressure (p_o) acting on the transducer is calculated by Eq. (2) using measured orthogonal strains. In contrast to the previous measuring method, this method using an embedded transducer is called the "Inner Pipe Method". The detail of sensory part of the transducer subjected to expansive pressure is shown in Fig. 1(c). The inner surface of the parts were reamed and orthogonal strain gauges attached. Electrical wires to the strain gauges were protected from contact with the expansive material by passing throughout the steel pipe. The sensory part attached the strain gauges and the protection parts of electrical wire were joined by threads. Two kinds of transducer were used in this tests: the A–type, with an outer diameter of 13.8 mm and an inner one of 9.5 mm; and the B–type, with an outer diameter of 17.4 mm and an inner one of 12.0 mm.

2.2 Diaphragm method

This measuring method was considered to measure directly on the expansive pressure in narrow grooves made by using a concrete cutter. A pressure transducer should be flat so that it can be inserted into a narrow groove. We have developed the diaphragm type transducer taking an idea, such as fluid/soil pressure transducers with the sensory part of diaphragm. To measure the expansive pressure is the same as the "Inner Pipe Method", since the transducer was embedded in the groove. The measuring system with this embedded transducer is called the "Diaphragm Method".

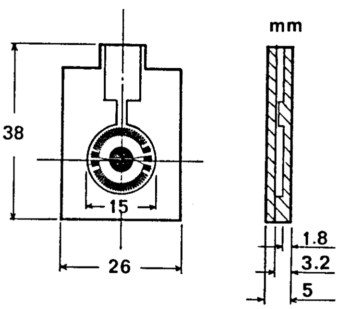


Fig. 2 Diaphragm Method (Sensory Part)

An example of sensory part of newly developed diaphragm transducer is shown in Fig. 2. At the center of steel plate of 3.2 mm thickness, a hole is made for a circular strain gauge (120Ω, 4 gauges activity) is attached on the surface of this diaphragm. The transducer consists of two thin steel plates one 3.2 mm thick; the other, 1.8 mm thick fixed with epoxy adhesive. In the design of the transducer, it is considered that the uniform expansive pressure "p" acts on the circular plate with fixed boundary. The relationship between the pressure acting on the diaphragm and the strain at the diaphragm is given by Eq. (3).

$$p = a \cdot \varepsilon \qquad (3)$$

The coefficient a was measured by the calibration test, using oil pressure. The value of a shows the sensitivity of the transducer and can be determined due to the thickness and the diameter of diaphragm. Two kinds of transducer have been made according to the degree of expansive pressure.

An example of calibration test results using oil pressure is shown in Fig. 3. Loading and unloading operations were repeated for 5 cycles. After repeated load testing, residual strain was only about $5x10^{-6}$. Moreover, the change in strain due to temperature was negligible. The influence of temperature when using the transducer will be neglected in practice, because even if a change of 30°C occurs, the change of expansive pressure is only 0.2 MPa. The diaphragm method has been developed only for measuring the expansive pressure in grooves; however, it can also be used to measure the expansive pressure in boreholes and describe elsewhere.

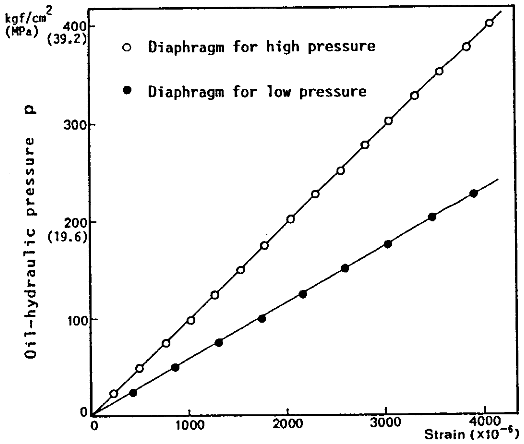


Fig. 3 Sample of Calibration

3. TESTS OF DIAPHRAGM METHOD

In the test of inner pipe method, to verify the accuracy of pressure transducer that can measure the expansive pressure acting on the inner surface of a borehole, a "double pipe test" was carried out. The purpose of this test is to compare the expansive pressure acting on the surface of the outer steel pipe (p_o) and the inner one (p_i) respectively. In this test, the inner pipe was set at the center of the outer steel pipe and the expansive demolition agent was poured into the space between the pipes. The values of p_o and p_i were calculated using Eq. (1) and Eq. (2) respectively, and it was found that the time dependent change of p_o and p_i was equal. In the test using the diaphragm method; to verify how accurately the pressure transducer can measure the expansive pressure in narrow grooves made with a concrete cutter, modified double pipe test was carried out similarly as above.

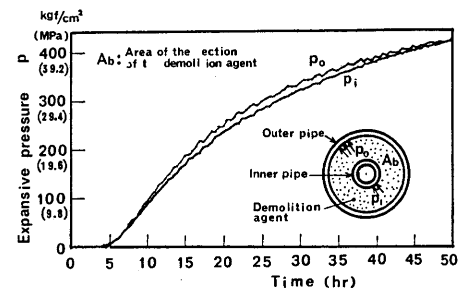
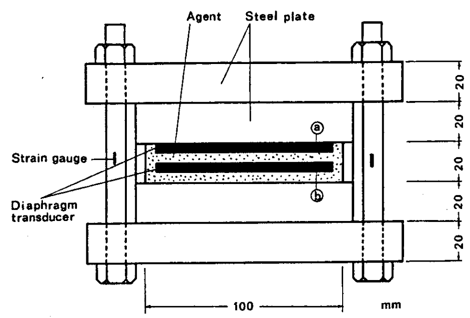


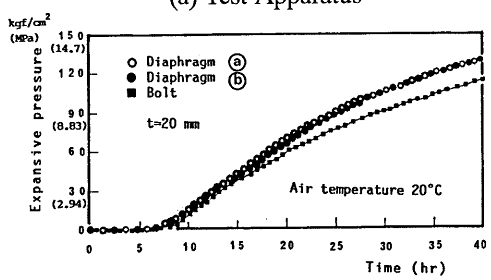
Fig. 4 Comparison of p_o and p_i in Double Pipe Test



(a) Test Apparatus

3.1 Experiment I

The apparatus to measure expansive pressure in grooves as shown Fig. 5(a), a groove 20 mm wide was fitted with steel plates in which a diaphragm transducer was mounted on the upper plate and the other one was set at the middle of the groove with 5 mm spacing. Expansive pressures acting on each transducer were measured after pouring the slurry into the groove. An example of expansive pressure–time relationship in a groove is shown in Fig. 5(b). From this



(b) Time–dependent Change of Expansive Pressure

Fig. 5 Result of Expansive Pressure in Modified Groove figure, we found that the values measured with diaphragm transducers agreed well with each other, but were slightly different from the values calculated from bolt strains.

3.2 Experiment II

Steel plates having a groove of 10 mm wide is similar to the one as shown Fig. 5(a) was set using rigid steel frame and pre-stressed with 1.96 MPa in axial direction. Expansive pressure in the axial direction was measured with a load cell and the diaphragm transducer. Compressive load based on expansion is measured by load cell and transformed into expansive pressure. Figure 6 shows the expansive pressure–time relationship. In this test, the diaphragm transducer was attached to one of the steel plates, the groove width was set at 5 mm between the steel plates, and slurry was poured into the groove. As shown in Fig. 6, the expansive pressure measured by the load cell shows constant value of 1.96 MPa up to the prestressing level. After reaching 1.96 MPa level, the expansive pressure measured by the load cell agrees well with the expansive pressure measured by the diaphragm transducer. From the results of experiments I and II, it was verified that we can measure the expansive pressure directly and accurately within narrow grooves made with a concrete cutter using the diaphragm method.

3.3 Experiment III

The diaphragm method has been developed for measuring expansive pressure in narrow grooves; however, it is also convenient to use a diaphragm transducer to measure expansive pressure in boreholes. As shown in Fig. 7(a), modified double pipe test, in which the diaphragm transducer was mounted in the outer steel pipe attached with orthogonal strain gauges, was carried out in a similar way to the inner pipe method. In Fig. 7(b), an example of the time dependent change of expansive pressure was shown. It is found that the expansive pressure acting on the inner surface of outer steel pipe (p_o) agree with expansive pressure (p_i) measured by the diaphragm type trans-

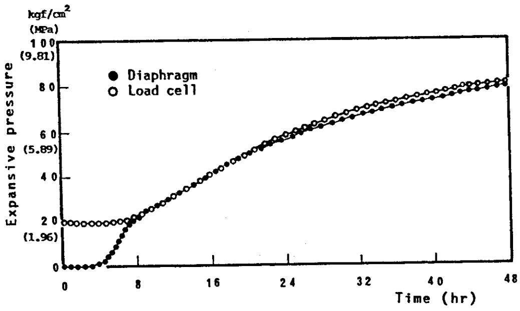


Fig. 6 Time-dependent Change of Expansive Pressure (Load Cell and Diaphragm Transducer)

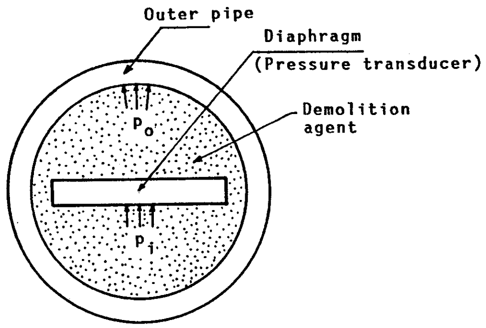


Fig. 7 (a) Outline of Modified Diaphragm Transducer

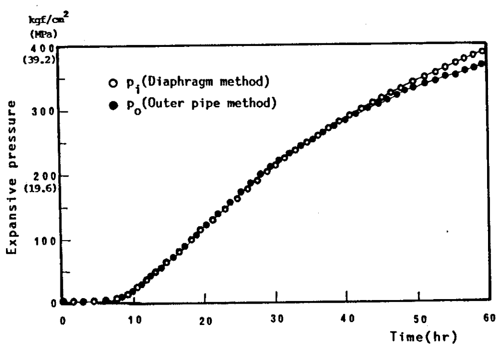


Fig. 7 (b) Comparison of Time-dependent Change of p_o and p_i

Table 1 Chemical Composition of Expansive Demolition agent

(w t %)

Igloss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Total
1. 3	8. 5	2. 0	0. 9	82. 9	0. 7	3. 3	99. 6

ducer. From these results, we can also measure the expansive pressure directly and accurately in boreholes.

Above all results show that expansive pressure is transmitted in a manner similar to that of fluid. Therefore, the diaphragm transducer can be applied to measure expansive pressure in elliptic boreholes. In the double pipe test using an inner pipe, the following results were obtained: i.e. the sum of axial tensile forces acting on inner pipe and outer one ($\sigma_{zo} \cdot A_{so} + \sigma_{zi} \cdot A_{si}$, where, A_{so}, A_{si} is the cross–sectional area of outer/inner steel pipe, the value of σ_{zo} ; σ_{zi} was calculated with σ_{zo} ; σ_{zi} $= E_s\,(\varepsilon_z + \nu_s \varepsilon_\theta)\,/(1 - \nu_s^2)$) are equal to the product of the radial expansive pressure and cross–sectional area of demolition agent ($p_i \cdot A_b$) [1],[2]. In the outer steel pipe test without inner pipe, the same results were also obtained. These results show that the axial expansive pressure acts in the same way as the radial expansive pressure, since the axial expansion was transmitted certainly to the steel pipe by the bond between the surface of steel and the hardened agent.

In all the above experiments, expansive demolition agent for use in summer supplied by Onoda Cement was used with a water–demolition agent ratio (W/B) = 25%. The chemical composition and main minerals of the expansive demolition agent are shown in Table 1. Experimental results shown later, also used the same type of agent.

4. INFLUENCE OF PHYSICAL RESTRAINT ON EXPANSIVE PRESSURE

The expansion of the demolition agent is caused by the chemical reaction; but, if there is no physical restraint of the boundary, the expansive pressure does not occur, and only the volume expands. The expansive pressure is regarded as the contact pressure which is caused by restraining the free expansion of volume.

4.1 Definition of restraint modulus

The relationship between internal pressure, p, and the circumferential strain ε_θ at the inner surface of a cylinder, such as boreholes is described in Eq. (4) using the elastic theory.

$$p = \frac{E_s(k^2-1)}{\{k^2+1-\nu_s(2-k^2)\}}\varepsilon_\theta = R \cdot \varepsilon_\theta \qquad (4)$$

where, E_s is Young's modulus of the steel pipe,
ν_s is Poisson's ratio of steel pipe, and
k is the ratio of the outer diameter to the inner diameter (k = outer diameter/inner diameter).

In Eq. (4), R is the restraint modulus. R is the degree of restraint to the internal pressure. The restraint modulus is a function of Young's modulus, Poisson's ratio, and the ratio of outer diameter to inner diameter of materials to be demolished. It has the same dimension as Young's modulus. When k > 5, the effect of k to R becomes small and negligible, the value of R is determined by Young's modulus and Poisson's ratio of the materials to be demolished.

4.2 Experimental results and discussions

4.2.1 In case of elastic restraint body

Since the restraint modulus is the function as Young's modulus and "k" is shown in Eq. (4), the influence of restraint modulus to expansive pressure by changing restraint modulus from case (1) to (4) were investigated experimentally.

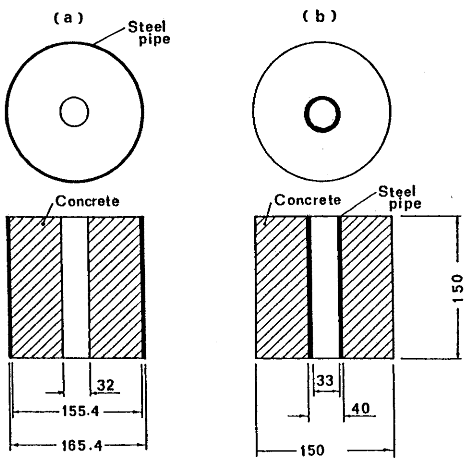


Fig. 8 (a) Concrete Restraint with Steel Pipe
Fig. 8 (b) Steel Pipe Restraint with Concrete

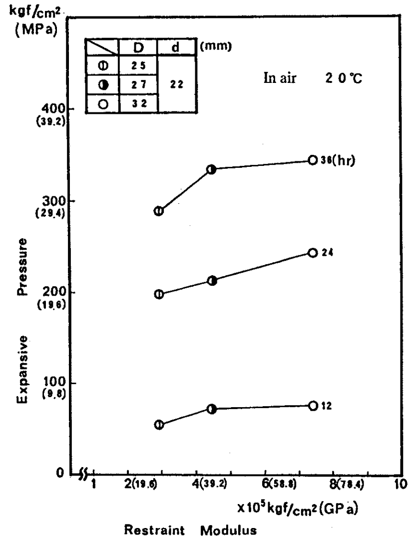


Fig. 9 Relationship between Expansive Pressure and Restraint Modulus

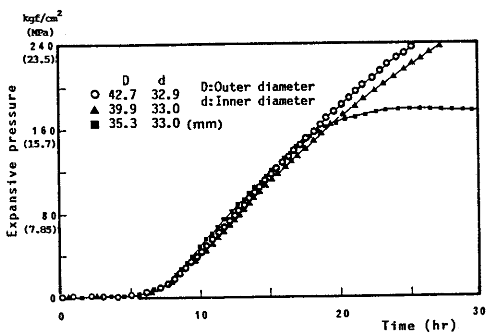


Fig. 10 Expansive Pressure of Various Restraints of Steel Pipe

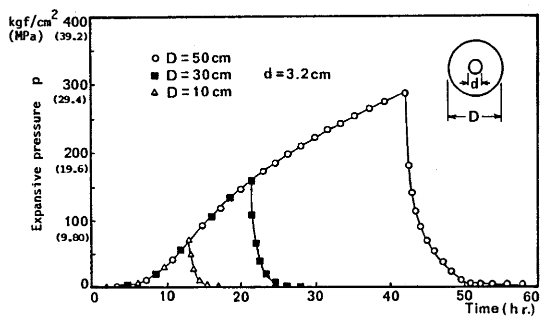


Fig. 11 Expansive Pressure in Concrete Cylinder with Various Outer Diameters

(1) When changing the wall thickness of steel pipe, the inner diameter is to be kept constant.
(2) When changing the outer diameter of concrete cylinder, the inner diameter is to be kept constant.
(3) In the case of steel pipe when filled with concrete. (Fig. 8(a))
(4) In the case of restraint with concrete cylinder around steel pipe. (Fig.8(b))

Figure 9 shows one of the result of case (1), in which the relation between the value of expansive pressure and the restraint modulus is plotted as a parameter of time. Expansive pressure was measured by outer pipe method with constant inner diameter 22 mm, the air temperature is at 20°C. Expansive pressure was slightly higher as the wall thickness of steel pipe increased.

On the other hand, figure 10 shows one of results using steel pipe in 33 mm diameter in air temperature at 20°C. The restraint modulus of outer steel pipe was 16, 41 and 54 (GPa) respectively, expansive pressure was measured by diaphragm method in this test. Thin walled pipe yielded on the way, but the three curves were plotted on the same curve up to yield point. When expansive pressure was larger, some increment of the restraint modulus was found, the influence of the temperature was considered because the temperature of heat of hydration was higher.

One of the results measured by diaphragm method in case (2) is shown in Fig. 11. These results were the time-dependent change of expansive pressure curves using concrete cylinders of 10, 30, and 50 cm outer diameter (inner diameter: 3.2 cm; height: 15 cm). As the changes of expansive pressure are plotted on the same curve, the influence of the restraint modulus cannot be found in this case, because even if the outer diameter of the concrete cylinder was large, the change of restraint modulus is small with only 21 to 25 (GPa). At the drop point of expansive pressure in Fig. 11, a crack occurred reaching to the outer surface of the concrete cylinder. It was observed that the expansive pressure was increasing steadily up to the fracture.

Experiments from case (1) to (4) were carried out at the same time to observed the expansive pressure-time relationship in 20°C air temperature. Also, the case of only using a steel pipe in case (4) was observed in air and in water at same temperature 20°C, respectively. At the condition in water, specimens filled with slurry were set in water, after pouring works immediately and the measurement was started. The diaphragm method was used in this test. Figure 12 shows the expansive pressure-time relation. It was found that changes of all expansive pressure until 40 hours were held among the upper change of expansive pressure using steel pipe in air and lower change in water.

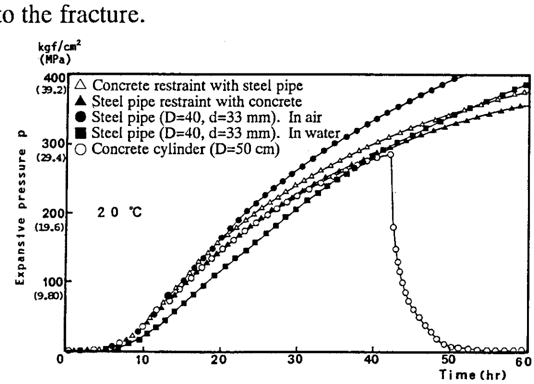


Fig. 12 Expansive Pressure of Various Restraint Moduli

Figure 13 shows the relation between the amount of expansive pressure and the restraint modulus as time parameter based on Fig.12. Although the restraint modulus was 25–84 (GPa) widely ranged, the influence of the restraint modulus was not observed in this figure. Regardless of the same ambient temperature 20°C and using the steel pipe with the same restraint modulus, the amount of expansive pressure in water 24 hours later was 4.9 MPa less than that in air; also, the value was about 10 to 20% lower than that in air, as shown in Fig. 9. This is considered to be due to the heat of hydration of the agent diffusing in water rather than in air, although the temperature is the same. The influence of temperature containing with the heat diffusion of hydration of the agent will describe in next chapter.

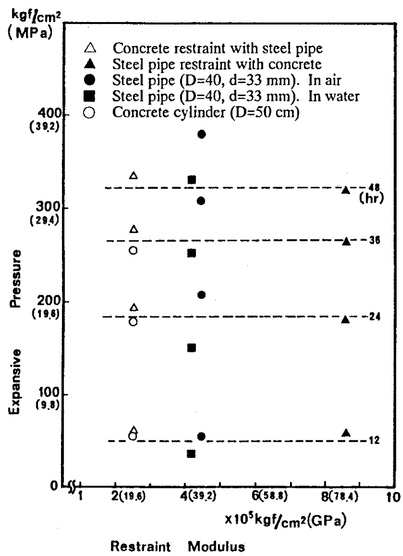
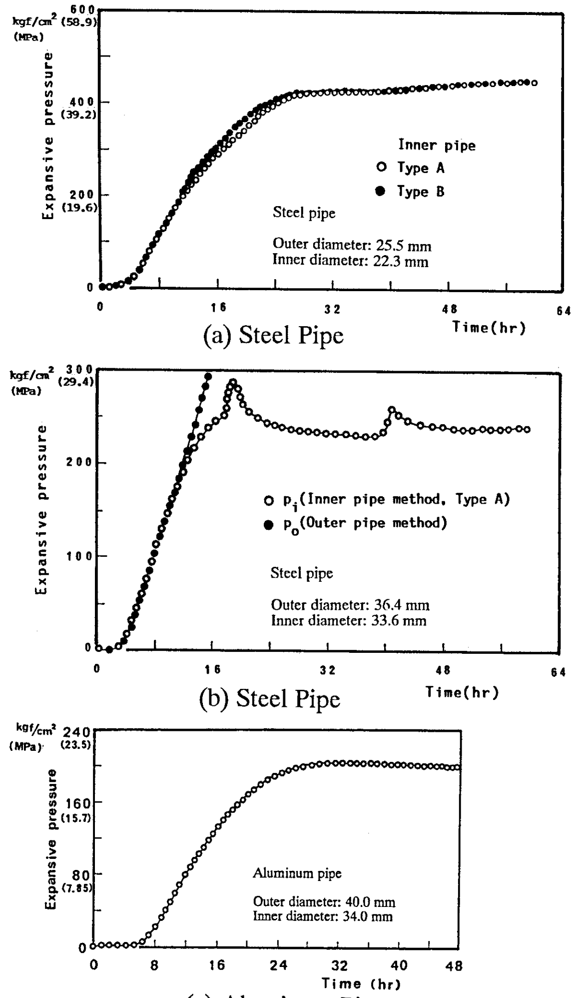


Fig. 13 Relationship between Expansive Pressure and Restraint Modulus

From above results, it seems that the influence of physical restraint to expansive pressure is smaller than that of temperature.

4.2.2 In case of elasto-plastic restraint body

If the restraint modulus of concrete cylinder specimens in 50 cm outer diameter and 3.2 cm inner one to be used in above experiment is assumed to the steel pipe with same restraint modulus. For example, the outer diameter of the steel pipe in 22.3 mm and 33.57 mm inner diameter is 24.9 mm and 37.1 mm, respectively. The thin-walled steel pipe yielded on reaching the yield pressure of the pipe, as shown in Fig. 14(a),(b). These facts indicate that the outer pipe method using steel pipe with the same restraint modulus as the material to be demolished cannot be measured exactly. The expansive pressure–time relationship shown in Fig. 14(c) was one of the results measured with a diaphragm transducer using aluminum pipe with a lower yield point instead of steel pipe. At constant pressure, it shows that the aluminum pipe yielded. Yield expansive pressures agreed well with the results of the oil pressure tests and the values were calculated using the equation $p_y = 2\tau_y \cdot \log_e k$ (where, τ_y is the yield shear stress of material, and k is the ratio of the outer diameter to the inner diameter of the pipe) from Ref.[4]. It was found that the inner pipe method and the diaphragm method were also reliable methods for measuring the yielding pressure of steel and aluminum pipe. From these figures, after the yield point of the pipe was reached, even if the expansive pressure decreased slightly, expansion increased in the state of maintained yield pressure. For example, when we measured the outer diameter of yielded aluminum pipe 60 hours later, an increase of 2 mm in the outer diameter to 40 mm the original diameter was observed. It was found that the capacity of expansion was very large.



(a) Steel Pipe

(b) Steel Pipe

(c) Aluminum Pipe

Fig. 14 Time–dependent Change of Expansive Pressure under Elasto–plastic Restraint Modulus

4.2.3 Local restraint with different restraint body

The behavior of expansive pressure locally restrained with a different restraint body was investigated. A concrete cylinder restrained at the center of hole with a steel pipe was used as a specimen. Time–dependent changes of expansive pressure in the concrete part and restrained with steel are shown in Fig. 15. Both changes of expansive pressure agreed well up to fracture of the concrete part. From this result, it seems also that the influence of restraint modulus to expansive pressure is rather small.

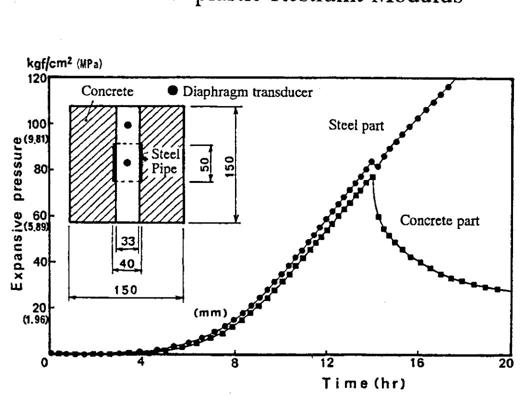


Fig. 15 Expansive Pressure in Steel and Concrete Portion

5. INFLUENCE OF TEMPERATURE TO EXPANSIVE PRESSURE

It seems that there are few reports investigating systematically the influence of temperature on expansive pressure, in spite of considering the influence of temperature on expansive pressure, because the expansion is caused by the hydration of CaO naturally. If the change in temperature affects the behavior of expansive pressure, it is necessary to understand the behavior of expansive pressure sufficiently, since the change in temperature affects the estimation of demolition time and another demolition design directly.

5.1 Relationship between surrounding ambient temperature and expansive pressure

Some results on the relationship between ambient temperature and expansive pressure measured by outer pipe method have already been reported as follows. The influence of air temperature to expansive pressure was remarkable; for example, expansive pressure at 30°C was 1.5 times higher than that at 20°C, 24 hours later, and when the temperature became higher, expansive pressure occurred earlier. To measure the temperature of the agent at the center of the borehole, thermocouples were mounted inside boreholes. The relationship between the temperature of the agent and the expansive pressure was examined as below.

Figure 16 shows the time dependent change of temperature of the agent corresponding to the one of expansive pressure under various restraint modulus as shown in Fig. 12. Comparing figure 16 with figure 12, it was found that when temperature of the agent was the highest in air temperature at 20°C, the expansive pressure was also highest; conversely, when temperature of the agent was lowest in water temperature at 20°C, the expansive pressure was also lowest. In other result, the expansive pressure is also higher as temperature increases, even at small difference of temperature. It was found that the temperature of the agent affected to expansive pressure obviously stronger than that of restraint modulus. In Fig. 16, the temperature of the agent using a steel pipe specimen in water was the same as the water temperature, and the drop points of temperature corresponded to water temperature when adjusted was made by thermostatic heater. Moreover, to examine the influence of temperature

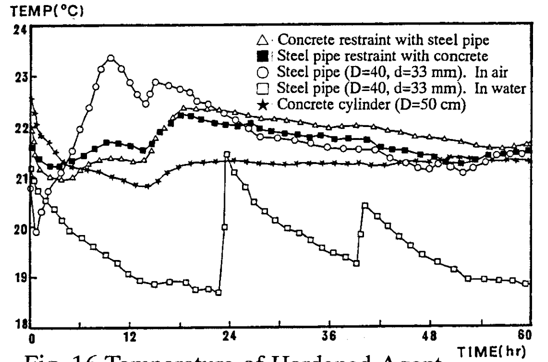


Fig. 16 Temperature of Hardened Agent under Various Restraint Moduli

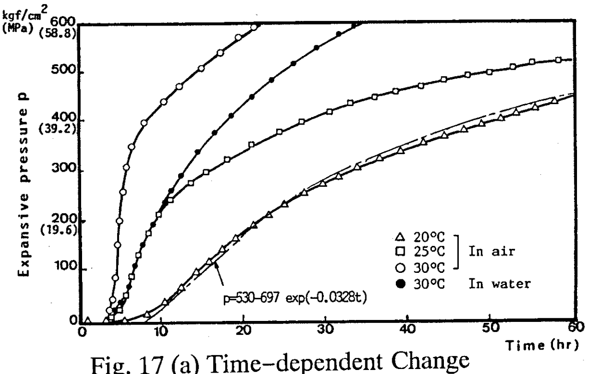


Fig. 17 (a) Time-dependent Change of Expansive Pressure

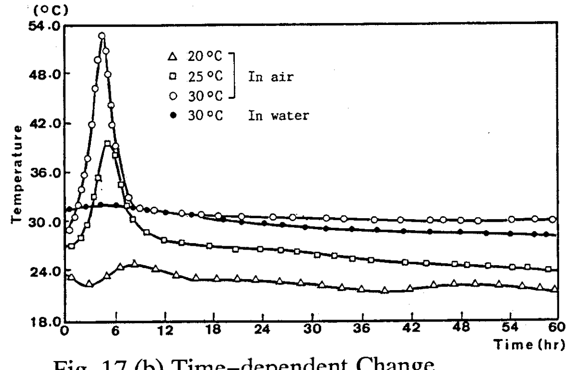


Fig. 17 (b) Time-dependent Change of Temperature of Hardened Agent on expansive pressure minutely; the relationship between the temperature of the agent and the expansive pressure were measured at temperatures of 20°C, 25°C, and 30°C both in air and in water. Experimental results were shown in Fig. 17. Above all, results concerning the influence of temperature to expansive pressure are summarized as follows:

(1) As the ambient temperature is higher, in air as well as in water, expansive pressure occurs earlier and rises steeply. Also, as the ambient temperature is higher, the expansive pressure is larger.

(2) If the ambient temperature is the same, the expansive pressure in air is higher than that in water.

(3) When in air temperature at 25°C, 30°C, the peak point of temperature reaching 40°C to 50°C appears 4 to 5 hours after pouring the slurry; the expansive pressure also increases remarkably. These peaks were caused by the heat of hydration of CaO.

(4) At an air temperature of 20°C, the obvious peak point was not observed as shown in 25°C, 30°C, and the temperature of the agent was only 1 to 2°C higher than air temperature. In water, the temperature of the agent was same as water temperature in all case. In concrete block, the temperature of the agent was same or slightly higher than that air temperature. In both the cases above, expansive pressure increased gradually.

To summarize the above results, it can be explained qualitatively that if the ambient temperature is higher, the expansive pressure increases rapidly, since the hydration reaction of CaO is accelerated; conversely, as the heat of hydration diffuses to the surrounding water or concrete, the expansive pressure increases slowly because the hydration reaction is not as active as in air.

5.2 Relationship between expansive pressure and degree of hydration of CaO

To evaluate the relationship of expansive pressure and temperature quantitatively, the degree of hydration of CaO, which was the main component of the expansive agent, was investigated. The slurry of expansive demolition agent (W/B = 25%) was poured into the steel pipe (outer diameter: 42.7 mm; inner diameter: 32.8 mm; length: 15 cm) and the upper and lower surfaces of pipe were restrained with steel plates, and then the expansive pressure and the degree of hydration were measured in water at 20°C and 30°C. After pouring, and passing time of 2, 6, 9, 24 and 66 hours, each sample of hardened agent was taken from the middle of the pipe, washed with acetone to stop hydration and "D" drying treatment were done.

A differential thermogravimeter was used to measure the weight loss attributable to dehydration of $Ca(OH)_2$ at around 460°C and to decarboxylation of $CaCO_3$. The $CaCO_3$ measurement was converted and added to the dehydration weight loss of $Ca(OH)_2$. This total dehydration loss of $Ca(OH)_2$ was converted into a weight percentage of $Ca(OH)_2$ in the hydrated agent remaining after "D" drying. This value included the amount of $Ca(OH)_2$ produced by the hydration of CaO (calcined lime) and other mineral components in the specimen. The degree of hydration of CaO was calculated as the percentage to the perfect hydration (100%) state when the specimen was set in water at 30°C for 66 hours and then cured in steam at 65°C for three days.

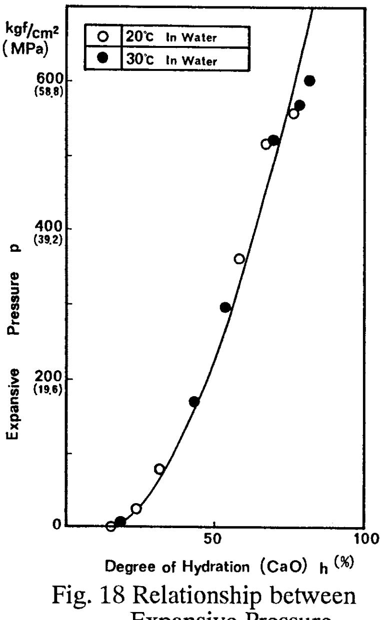


Fig. 18 Relationship between Expansive Pressure and Degree of Hydration of CaO

Figure 18 shows the relationship between the expansive pressure and the degree of hydration of CaO. From this figure, it was found that, when the relation is plotted on the same curve, it is independent of temperature. This result shows that expansive pressure can be evaluated using the degree of hydration even if the ambient temperature is changed. It has been reported by Yamasaki et al. [5] that the time dependent change of expansive pressure was similar to the one that of hydration of free–lime by using the other kind of agent. Equation (5) below, on the expansive pressure–degree of hydration relationship was obtained by the least square program.

$$p = 128.9(h/100 - 0.14)^{1.68} \quad (5)$$

where, p is the expansive pressure (MPa), and h is the degree of hydration of CaO (%).

5.3 Estimation method of expansive pressure with changing of temperature

The time dependent change of degree of hydration was described approximately by equations (6) and (7) at 20°C, 30°C respectively.

$$h/100 = t/(10.6 + 1.55t) \quad \text{(at 20°C)} \quad (6)$$

$$h/100 = t/(8.65 + 1.02t) \quad \text{(at 30°C)} \quad (7)$$

An example of the estimation method of expansive pressure with changing of temperature such as Fig. 19(a) is also shown in Fig. 19(b).

In Fig. 19(b), the time–dependent curve of hydration at 20°C is maintained until "t_A", and the curve of "AB" is obtained by shifting parallel the part "DE" of the time–dependent curve of hydration at 30°C in the section from "t_A" to "t_B", since the degree of hydration at point "D" is same at the point "A", and point "E" is also corresponding to point "B". When the temperature is changed again to 20°C, the curve of "BC" is also obtained by shifting the curve "FG" of the time–dependent curve of hydration at 20°C. It can be considered that "OABC" is the time–dependent curve of hydration when temperature is changed as shown above. This estimation method is similar to that Uchida et al. [6] used to express the cumulative heat liberation model of cement when the temperature of the system was changed in steps from 20°C to 40°C. When the degree of hydration is determined, the expansive pressure is calculated from Eq. (5).

Figure 20 shows an example of the time dependent change of expansive pressure by comparing measured values with the predicted curve when water temperature is changed. Surrounding water temperature was 20°C until 15 hours, and was 30°C until 30 hours and was constant at 20°C thereafter. The predicted values agree with the measured ones. It is found that the above method can precisely determine the expansive pressure accompanying the change of temperature. Equations (5),(6), and (7) were used to calculate the above prediction curve. It can be estimated accurately the time–dependent change of expansive

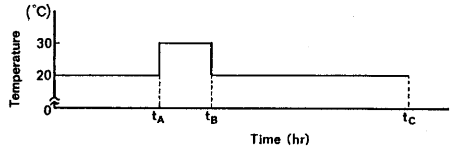


Fig. 19 (a) Change of temperature

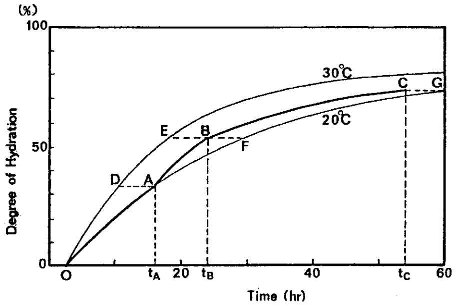


Fig. 19 (b) Time–dependent change of hydration

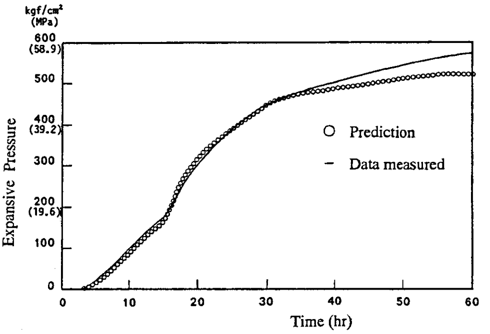


Fig. 20 Comparison of Predicted and Measured Expansive Pressure at Temperature Changes

pressure with complex changing of temperature, if the time– dependent changes of the hydration curves are measured under various temperature.

6. MECHANICS OF EXPANSIVE PRESSURE

From above results, two interesting characteristics of expansive pressure were obtained as follows;
(1) Expansive pressure is transmitted in a manner similar to that of fluid.
(2) The influence of the physical restraint of surrounding materials is very small.
The reason for the above characteristics is considered to be that the elastic modulus of the hardened agent is small rather than that of the restraint materials. The following analytical approach was carried out based on the some considerations.

Now, let us consider the behavior of expansive pressure in double pipe test as shown in Fig. 21. The outer and inner pipes are steel, and the space between both pipes is filled with the slurry of the agent. If there is no restraint, free volume expansion only occurs and the ratio of expansion is about two times to the original volume, and then, the slurry becomes hardened at the initial stage, but after several hours it will destroy itself by expansion. Eventually, some restraint modulus is necessary to become solid state so that the expansive pressure occurs. The hardened agent is assumed that the elastic body having Young's modulus E_b and Poisson's ratio ν_b expands with expansion strain per unit volume β , and then the expansive pressure acting on the outer pipe and inner one is p_o and p_i respectively. The ratio p_o/p_i calculated by thick–walled cylinder theory is expressed by Eq. (8).

$$p_o/p_i = \frac{(1+\beta)(1+\nu_b)+\{(k_i^2+1)/(k_i^2-1)+\nu_{si}\}/n_i}{(1+\beta)(1+\nu_b)-\{(k_o^2+1)/(k_o^2-1)+\nu_{so}\}/n_o} \tag{8}$$

where, $n_i = E_{si}/E_b$, $n_o = E_{so}/E_b$

$k_i = r_{2si}/r_{1si}$, $k_o = r_{2so}/r_{1so}$.

When Young's modulus, E_b, is negligibly small compared with that of the restraining material, i.e., when the value of n_i, n_o is infinite, the ratio p_o/p_i equals unity, because both second terms of numerator and denominator in Eq. (8) become zero. It is analytically shown that the expansive pressure is transmitted in a manner similar to that of fluid.

The hardened agent was removed from the steel pipe (outer diameter: 42.7 mm, inner diameter: 32.8 mm) as the remaining cylinder shape when fixed expansive pressure occurred, and the compressive test was carried out immediately to measure Young's modulus and Poisson's ratio of the hardened agent using orthogonal strain gauges. When p = 19.6 MPa, E_b = 4.1 GPa, and when p = 39.2 MPa, E_b = 6.4 GPa, so that Poisson's ratio was 0.37 in both cases. From these data, the assumption that the hardened agent is an elastic body having a lower Young's modulus was found to be true. When using the assumed values in a double pipe test with steel pipe, i. e., substituting E_b = 4.1 GPa, ν_b= 0.37, k_o = 1.3, k_i = 1.38, β = 3000x10^{-6} into Eq. (8), the ratio p_o/p_i become 1.12. When the restraint material is concrete in which n_o = 10 and k_o > 5 usually, the ratio of p_o/p_i become 1.15. Both

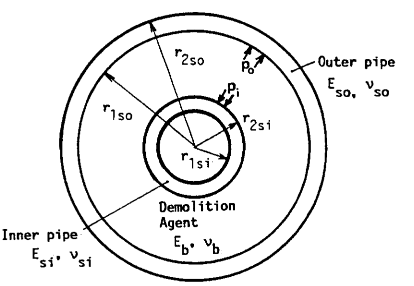


Fig. 21 Details of Double Pipe Test

calculated ratio p_o/p_i is about 15% larger, however it is considered that the ratio p_o/p_i approaches unity due to the effect of creep, because the hardened agent is also subjected to the same high expansive pressure itself constantly as acting on the inner surface of borehole. When the creep coefficient is ϕ , the effective modulus of elasticity of hardened agent is expressed as $E_b/(1+\phi)$, and then both the second terms of numerator and denominator in Eq. (8) become to small and negligible. It was also proved numerically that expansive pressure is transmitted in a manner similar to that of fluid.

Also, in the double pipe test, from the relationship between expansive pressure ratio p_o/p_i and cross-sectional area ratio A_b/A_i of the slurry of the agent considering various diameters of outer pipe as shown in Fig. 22; it was found that p_o/p_i is hardly influenced by A_b/A_i. This reason is considered that there is no factor concerning A_b/A_i in Eq. (8).

The relationship between expansive pressure p_o and expansion strain, β , is expressed by Eq. (9) when using steel pipe without inner pipe.

$$p_o=\frac{E_{so}\cdot\beta}{(1-\nu_b)(1+\beta)n_o+(k_o^2+1)/(k_o^2-1)+\nu_{so}} \qquad (9)$$

When the restraint modulus is infinite ($E_{so}\rightarrow\infty$), equation (9) is simplified to Eq. (10).

$$p_o=\frac{E_b\cdot\beta}{(1-\nu_b)(1+\beta)} \qquad (10)$$

In Eq. (10), if measured values such as E_b = 4.1 GPa, ν_b= 0.37 are given when p_o = 19.6 MPa, the expansion strain β is can be calculated.

The relationship between expansive pressure and restraint modulus is introduced as shown in Fig. 23 from equations (9) and (4), by using two measured values (E_b, ν_b) and calculated expansion strain β . It is found that the curve changed loosely and the influence of restraint modulus to the amount of expansive pressure become small, when the restraint modulus is larger than 20 GPa. These facts can be also found in the experimental results. Furthermore, when Young's modulus E_b is assumed smaller 1/2 to 1/3 by considering the influence of creep of hardened agent, the influence of restraint modulus to expansive pressure become rather small.

It is considered that Young's modulus and the expansion strain β are time dependent and affected by temperature, and also, creep of hardened agent is the function of expansive pressure, age, temperature; and these factors influence each other, expansive pressure occurs under the complex coupling conditions.

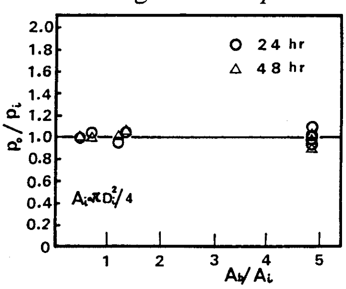


Fig. 22 Relationship between p_o/p_i and A_b/A_i

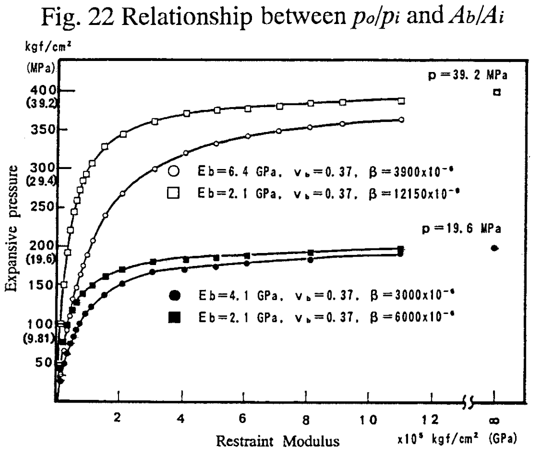


Fig. 23 Relationships between Expansive Pressure and Restraint Modulus (Analytical)

However, the above model, in which the physical properties of the hardened agent are treated as constant values is considered to be adequate.

7. CONCLUSIONS

The results of these studies are summarized below.

(1) The authors have newly developed a method of measuring expansive pressure using embedded pressure transducers called the "Inner Pipe Method" and the "Diaphragm Method". These transducers can measure the expansive pressure in a borehole directly and accurately while containing the influence of ambient temperature. Also, these transducers can be simpler to treat.

(2) Expansive pressure is greatly affected by the ambient temperature; however, the influence of the restraint modulus seems to be small.

(3) On the influence the ambient temperature to the expansive pressure; it can be explained qualitatively that if the ambient temperature is higher, or the heat of hydration diffused to surrounding materials is smaller, expansive pressure increase rapidly and highly, since the hydration reaction of CaO is accelerated.

(4) The relationship between expansive pressure and degree of hydration of CaO is expressed by the equation $p = 128.9(h/100 - 0.14)^{1.68}$ in spite of the ambient temperature. Even if the ambient temperature is variable, the expansive pressure can be calculated accurately using above equation when the degree of hydration is determined at that point.

(5) Assuming an elastic body with a lower Young's modulus (1 GPa order) and a large capacity of expansion under the restraint condition, experimental results which expansive pressure is transmitted in a manner similar to that of fluid, and the influence of the physical restraint of surrounding materials is very small can be explained analytically.

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